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$K_L \to \pi^0 \nu\bar{\nu}$ as a Probe of New Physics

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Abstract

We summarize the theoretical virtues of the rare $K \to \pi\nu\bar{\nu}$ decays and emphasize the unique role of $K_L \to \pi^0\nu\bar{\nu}$ in probing the nature of physics beyond the Standard Model, in particular concerning possible new sources of CP violation and flavor-symmetry breaking. A brief summary of the prospects for the measurement of the $K_L \to \pi^0\nu\bar{\nu}$ rate is also given.

1 Introduction

The rare decays of K and B mesons play an important role in the search for the underlying mechanism of flavor dynamics and in particular in the search for the origin of CP violation [1]. Among the many K and B decays, the rare decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ are very special as their branching ratios can be computed to an exceptionally high degree of precision, not matched by any other flavor-changing neutral-current (FCNC) process involving quarks. While the theoretical uncertainties in the branching ratios of prominent FCNC processes, such as $B \to X_s\gamma$ and $B \to X_s\mu^+\mu^-$, amount to $\pm 10\%$ or larger, the irreducible theoretical uncertainty in $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ amounts to only 1-2% [2, 3, 4, 5]. The non-negligible charm contribution leads to a slightly larger

theoretical error in the case of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$: $\pm 8\%$ at the NLO level [4, 6], which will soon be reduced significantly thanks to both the NNLO calculation of the leading partonic amplitude [7] and the recent progress in the evaluation of long-distance effects [8]. A recent very detailed review of $K^+ \to \pi^+\nu\bar{\nu}$ and $K_{\rm L} \to \pi^0\nu\bar{\nu}$ in the Standard Model and in its most popular extensions has been presented in [9], where the usefulness of both processes for the determination of the SM parameters and in the search for the physics beyond the SM has been emphasized and summarized. Other theoretical reviews can be found in [10], while the prospects for the measurements of these decays have been summarized in [11, 12].

According to the detailed analysis in [9], the present predictions for the branching ratios of the two decay modes within the SM are

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\rm SM} = (7.8 \pm 1.2) \cdot 10^{-11} \ , \tag{1.1}$$

$$\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})_{\rm SM} = (3.0 \pm 0.6) \cdot 10^{-11} \ , \tag{1.2}$$

where a good fraction of the error ($\pm 15\%$ and $\pm 20\%$, respectively) is due to parametric uncertainties (CKM angles and quark masses). Thanks to the foreseen theoretical progress in the evaluation of $K \to \pi\nu\bar{\nu}$ amplitudes and, especially, the expected improvement in the determination of the CKM parameters from BaBar, Belle, CDF, D0, and other experiments, these predictions should reach the $\pm 5\%$ level, or better, in a few years. This accuracy cannot be matched by any other loop-induced process in the field of meson decays.

On the experimental side, the AGS E787 and E949 collaborations at Brookhaven observed the decay $K^+ \to \pi^+\nu\bar{\nu}$ [13, 14, 15] finding three events so far. The resulting branching ratio is

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (14.7^{+13.0}_{-8.9}) \cdot 10^{-11} \ . \tag{1.3}$$

The central value of this measurement is substantially higher than the SM prediction in (1.1). However, taking into account the substantial uncertainties in (1.3), as well as theoretical and parametric errors, the present result is consistent with the SM expectation.

So far, the best direct experimental information on the $K_{\rm L} \to \pi^0\nu\bar{\nu}$ mode is the KTeV bound: $\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu}) < 5.9 \cdot 10^{-7}$ [16], which is about four orders of magnitude above the SM expectation. A more stringent constraint can be derived using the information on the charged mode and isospin symmetry [17]:

$$\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu}) \lesssim \frac{\tau_{K_L}}{\tau_{K^+}} \mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) \tag{1.4}$$

which through (1.3) gives

$$\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu}) < 1.4 \cdot 10^{-9} \qquad (90\%\text{C.L.}). \tag{1.5}$$

As discussed in [17], this bound is valid in virtually any extension of the SM. By comparing this model-independent bound and the SM prediction in (1.1), it is clear that there is still much room for new physics in $K_L \to \pi^0\nu\bar{\nu}$. As we shall discuss in the following, this corresponds to unexplored regions in the parameter space of several realistic new physics scenarios. But even if the experimental measurement of $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ were found in agreement with the SM expectation with a small relative error, this information would translate into a *unique* and precious insight about the CP and flavor structure of any extension of the SM. These features makes the experimental search for $K_L \to \pi^0\nu\bar{\nu}$, at the SM level and below, a win–win opportunity.

2 $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ within the SM

The main reason for the exceptional theoretical cleanness of $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ [18] decays is the fact that –within the SM– these processes are mediated by electroweak amplitudes of $O(G_F^2)$, which exhibit a power-like GIM mechanism [19] (see Fig. 1). This property implies a severe suppression of non-perturbative effects [5, 8, 20, 21, 22].[1] By comparison, it should be noted that typical loop-induced amplitudes relevant to meson decays are of $O(G_F\alpha_s)$ (gluon penguins) or $O(G_F\alpha_{\rm em})$ (photon penguins), and have only a logarithmic-type GIM mechanism, which implies a much less severe suppression of non-perturbative effects. A related important virtue, following from this peculiar electroweak structure, is the fact that $K \to \pi\nu\bar{\nu}$ amplitudes can be described in terms of a single effective operator:

$$Q_{sd}^{\nu\nu} = \bar{s}\gamma^\mu(1-\gamma_5)d\ \bar{\nu}\gamma_\mu(1-\gamma_5)\nu\ . \tag{2.1}$$

The hadronic matrix elements of $Q_{sd}^{\nu\nu}$ relevant to $K \to \pi\nu\bar{\nu}$ amplitudes can be extracted directly from the well-measured $K^+ \to \pi^0 e^+\nu$ decays, including isospin breaking corrections [24].

In view of these features, the measurements of the two $K \to \pi\nu\bar{\nu}$ branching ratios can be translated –within the SM– into precise information on the CKM matrix and, in particular, on the so-called CKM unitarity triangle [25]. As shown in Fig. 1, $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ determines the height of this triangle, while $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ determines one of its sides. Assuming that both branching ratios will be known to within $\pm10\%$, one expects the following accuracy on various quantities of interest [9]:

$$\sigma(\sin 2\beta) = \pm 0.05, \quad \sigma({\rm Im}\lambda_t) = \pm 5\%, \quad \sigma(|V_{td}|) = \pm 7\%, \quad \sigma(\gamma) = \pm 11^\circ\ . \tag{2.2}$$

[1] Higher-order electroweak effects on the leading $O(G_F^2)$ amplitude have also been computed and found to be safely negligible [23].

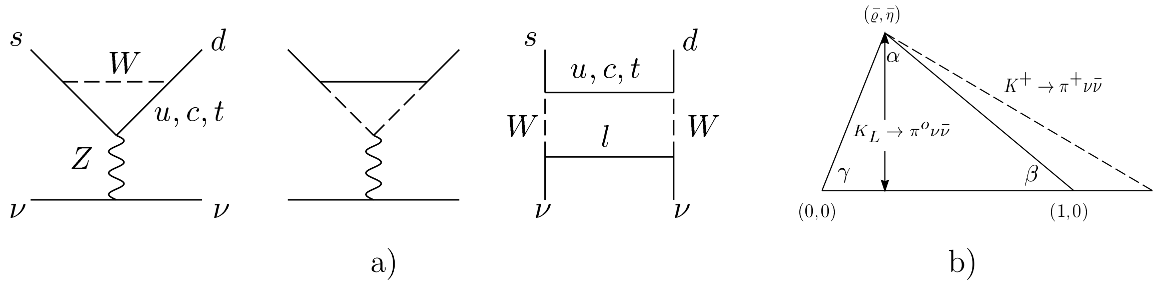

Figure 1: Leading Feynman diagrams relevant to $K \to \pi\nu\bar{\nu}$ decays (a); CKM unitarity triangle from $K \to \pi\nu\bar{\nu}$ (b).

where $\lambda_t = V_{ts}^* V_{td}$, with V_{ij} being the elements of the CKM matrix and (β, γ) the angles of the unitarity triangle (see Fig. 1). With the measurements of the branching ratios at the $\pm 5\%$ level these estimates change to

$$\sigma(\sin 2\beta) = \pm 0.03, \quad \sigma(\mathrm{Im}\lambda_t) = \pm 3\%, \quad \sigma(|V_{td}|) = \pm 4\%, \quad \sigma(\gamma) = \pm 6^\circ \ . \tag{2.3}$$

Further details can be found in [9].

It is worth stressing that the determination of CKM parameters via $K \to \pi\nu\bar{\nu}$ decays is mainly an efficient way to compare the measured value of these clean FCNC transitions with other clean tree-level mediated or loop-induced observables. Since the loop-induced observables are potentially affected by non-standard contributions, this comparison offers a powerful tool to constrain or identify new-physics effects. For instance, one of the most interesting studies which could be performed with experimental data on the two branching ratios, is a test of the so-called "golden relation" [26]:

$$(\sin 2\beta)_{\psi K_S} = (\sin 2\beta)_{\pi\nu\bar{\nu}} \ . \tag{2.4}$$

Here the right-hand side stands for the value of $\sin 2\beta$ determined from the two $K \to \pi\nu\bar{\nu}$ rates (see Fig. 1), while the left-hand side denotes the corresponding value extracted at B factories from the time-dependent CP asymmetry in $B_d^0 \to \psi K_S$. This relation is not only a very powerful tool to falsify the SM, but also a useful handle to discriminate among different new-physics scenarios.

A key feature of the $K_{\rm L} \to \pi^0\nu\bar{\nu}$ mode is the fact that it proceeds through a pure loop-induced *direct*-CP-violating amplitude [18]. Within the SM, its rate gives the cleanest determination of $\mathrm{Im}\lambda_t$, or the combination of Yukawa couplings which control the amount of CP violation in the model [27]. We can indeed write [25]

$$\mathrm{Im}\lambda_t = 1.39 \cdot 10^{-4} \left[\frac{|V_{us}|}{0.224}\right] \left[\frac{1.53}{X(x_t)}\right] \sqrt{\frac{\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})}{3 \cdot 10^{-11}}} \ , \tag{2.5}$$

where $X(x_t)$, with $x_t = m_t^2/M_W^2$, is the leading coefficient function of the operator $Q_{sd}^{\nu\nu}$ (according to the present value of the top-quark mass, $X(x_t) = 1.53 \pm 0.04$). Contrary to the $K_{\mathrm{L}} \to \pi^0\nu\bar{\nu}$ case, in essentially all other K and B meson decays the extraction of loop-induced direct-CP-violating amplitudes is subject to sizable (if not huge) non-perturbative effects. This is, for instance, the case of the currently popular direct CP-violating studies in non-leptonic two–body B decays, both those involving time-dependent distributions and those involving branching ratios and charge asymmetries. Either the processes are tree-level dominated (and thus naturally insensitive to new-physics effects) or it is very difficult to determine their direct-CP-violating phases with good theoretical control.

3 The unique role of $K_{\mathrm{L}} \to \pi^0\nu\bar{\nu}$ in probing physics beyond the SM

3.1 Preliminaries

There are several reasons why the decay $K_{\mathrm{L}} \to \pi^0\nu\bar{\nu}$ plays a special role in the investigation of possible physics beyond the SM. While some of these reasons have been already emphasized in the literature, we would like to stress here a few points that we find particularly important:

- The clean theoretical character of $K_{\mathrm{L}} \to \pi^0\nu\bar{\nu}$ (similarly of $K^+ \to \pi^+\nu\bar{\nu}$) remains valid in essentially all extensions of the SM, whereas this is generally not the case for non-leptonic two-body B decays used to determine the CKM parameters through CP asymmetries and/or other strategies. While several mixing induced CP asymmetries in non-leptonic B decays within the SM are essentially free from hadronic uncertainties, as the latter cancel out due to the dominance of a single CKM amplitude, this is often not the case in extensions of the SM in which the amplitudes receive new contributions with different weak phases implying no cancellation of hadronic uncertainties in the relevant observables.

- The theoretically clean determinations of CP-violating phases in non-leptonic B decays are based on tree level decays that are quite generally insensitive to new physics in the decay amplitudes and can be affected only by new phases in $B^0 - \bar{B}^0$ mixing. In $K_{\mathrm{L}} \to \pi^0\nu\bar{\nu}$ the contributions from the CP violation in $K^0 - \bar{K}^0$ mixing are by several orders of magnitude smaller than the direct CP violation in the decay amplitude [18] and consequently the direct CP violation in the SM and in its extensions can be tested here in a very clean environment. Due to the different

structure of the corresponding electroweak amplitudes, new-physics effects could be quite different in direct- and indirect-CP-violating amplitudes (see e.g. [28]). The former are poorly tested so far, because of the sizable non-perturbative uncertainties which affect non-leptonic process both in B and K decays. This implies that there is still much room in the new-physics parameter space which can only be explored by means of $K_{\rm L} \to \pi^0 \nu\bar{\nu}$.

- One of the most popular (and well motivated) scenarios about the flavor structure of physics beyond the SM is the so-called *Minimal Flavor Violation* (MFV) hypothesis [29, 30]. Within this framework (which can be regarded as the most *pessimistic* case for new-physics effects in rare decays), flavor- and CP-violating interactions are induced only by terms proportional to the SM Yukawa couplings. This implies that deviations from the SM in FCNC amplitudes rarely exceed the O(20%) level, or the level of irreducible theoretical errors in most of the presently available observables, although model independently effects of order 50% cannot be excluded at present [31]. Moreover, theoretically clean quantities such as $a_{\rm CP}(B \to J/\Psi K_S)$ and $\Delta M_{B_d}/\Delta M_{B_s}$, which measure only ratios of FCNC amplitudes, turn out to be insensitive to new-physics effects. Within this framework, the need for additional clean and precise information on FCNC transitions is therefore even more important. A precise measurement of $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ would offer a unique opportunity in this respect.

3.2 General parameterization and phenomenological considerations

An important consequence of the first item in the above list, is the fact that in most SM extensions the new physics contributions in $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_{\rm L} \to \pi^0 \nu\bar{\nu}$ can be parameterized in a model-independent manner by just two parameters, the magnitude and the phase of the Wilson coefficient of the operator $Q_{sd}^{\nu\nu}$ in Eq. (2.1).[2] More explicitly, we can encode all the new-physics effects around and above the electroweak scale into an effective Hamiltonian of the type ($\lambda_t = V_{ts}^* V_{td}$)

$$\mathcal{H}_{eff}(M_W^2) = \frac{G_F^2 M_W^2}{2\pi^2}\, \lambda_t \; X \; Q_{sd}^{\nu\nu} \;+\; [\text{non-FCNC terms}] \;+\; \text{h.c.} \qquad (3.1)$$

where the short-distance function [33]

$$X = |X| e^{i\theta_X} \qquad (3.2)$$

[2] For a discussion about the scenarios where this parameterization does not hold, see [32].

is such that the SM case corresponds to $|X| \to X(x_t) = 1.53 \pm 0.04$ and $\theta_X \to 0$. The important virtue of the $K \to \pi\nu\bar{\nu}$ system is that $|X|$ and θ_X can be extracted from $\mathcal{B}(K_\mathrm{L} \to \pi^0\nu\bar{\nu})$ and $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ without hadronic uncertainties, while the function X can be calculated in any extension of the SM within a perturbative framework.

The modulus of X is directly constrained by $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$, which is not very sensitive to θ_X, while $\mathcal{B}(K_\mathrm{L} \to \pi^0\nu\bar{\nu})$ strongly depends on θ_X. A non-vanishing value of θ_X would signal the presence of extra CP-violating phases in $K \to \pi\nu\bar{\nu}$ amplitudes in addition to the standard CKM phase. In general, we can write

$$\frac{\mathcal{B}(K_\mathrm{L} \to \pi^0\nu\bar{\nu})}{\mathcal{B}(K_\mathrm{L} \to \pi^0\nu\bar{\nu})_\mathrm{SM}} = \left|\frac{X}{X_\mathrm{SM}}\right|^2 \left[\frac{\sin(\beta - \theta_X)}{\sin(\beta)}\right]^2 , \tag{3.3}$$

where $\beta \approx 23^\circ$ is the standard angle of the unitarity triangle (or the phase of the CKM factor $V_{ts}^* V_{td}$). At present, the first factor on the right-hand side of Eq. (3.3) is constrained by the experimental data on $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ to be smaller than ≈ 7 (at 90% C.L.). However, even with an infinitely precise and completely SM result for $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$, one would still have much room for possible enhancements in $\mathcal{B}(K_\mathrm{L} \to \pi^0\nu\bar{\nu})$ due to the second factor, which could be as large as ≈ 6. Combining these two possible enhancement factors, one recovers the present large potential for enhancement of $\mathcal{B}(K_\mathrm{L} \to \pi^0\nu\bar{\nu})$ over its SM prediction, as also derived by the comparison of (1.2) and (1.5). The pattern of the two $K \to \pi\nu\bar{\nu}$ branching ratios as a function of θ_X is illustrated in Fig. 2. Note, in particular, that the ratio of the two modes depends very mildly on $|X|$ and provides the ideal tool to extract the non-standard CP-violating phase θ_X.

The X function has been defined assuming the SM normalization (electroweak couplings + CKM factors) for the $Q_{sd}^{\nu\nu}$ operator. In principle, the non-standard effects could originate through a very different type of dynamics, such that this normalization would not be the most natural one. To estimate the new-physics sensitivity of $\mathcal{B}(K_\mathrm{L} \to \pi^0\nu\bar{\nu})$ on pure dimensional grounds, we can denote by $\lambda_{sd}/\Lambda_\mathrm{NP}^2$ the overall coefficient of the extra (non SM) contribution to the $Q_{sd}^{\nu\nu}$ operator. If the generic dimensionless coupling λ_{sd} is of $O(1)$, it follows that a measurement of $\mathcal{B}(K_\mathrm{L} \to \pi^0\nu\bar{\nu})$ with 10%–20% accuracy allows probing new-physics scales well above 100 TeV. To be more precise, a measurement of $\mathcal{B}(K_\mathrm{L} \to \pi^0\nu\bar{\nu})$ with central value equal to the SM prediction and relative precision $p = \sigma\mathcal{B}/\mathcal{B}$, allows setting the following 90% CL bound on the scale of the operator:

$$\Lambda_\mathrm{NP}/\sqrt{\mathrm{Im}\lambda_{sd}} \;>\; \left[\frac{G_F^2 M_W^2}{2\pi^2}\mathrm{Im}\lambda_t X(x_t)\right]^{-1/2} (0.64\; p)^{-1/2} \;\stackrel{p=0.1}{\longrightarrow}\; 1280 \text{ TeV !} \tag{3.4}$$

This remarkably high scale corresponds to the effective mass of new particles only in the extreme scenarios where new physics effects contribute to $K_\mathrm{L} \to \pi^0\nu\bar{\nu}$ at the tree level and all the relevant couplings are $O(1)$. As discussed in the following sections,

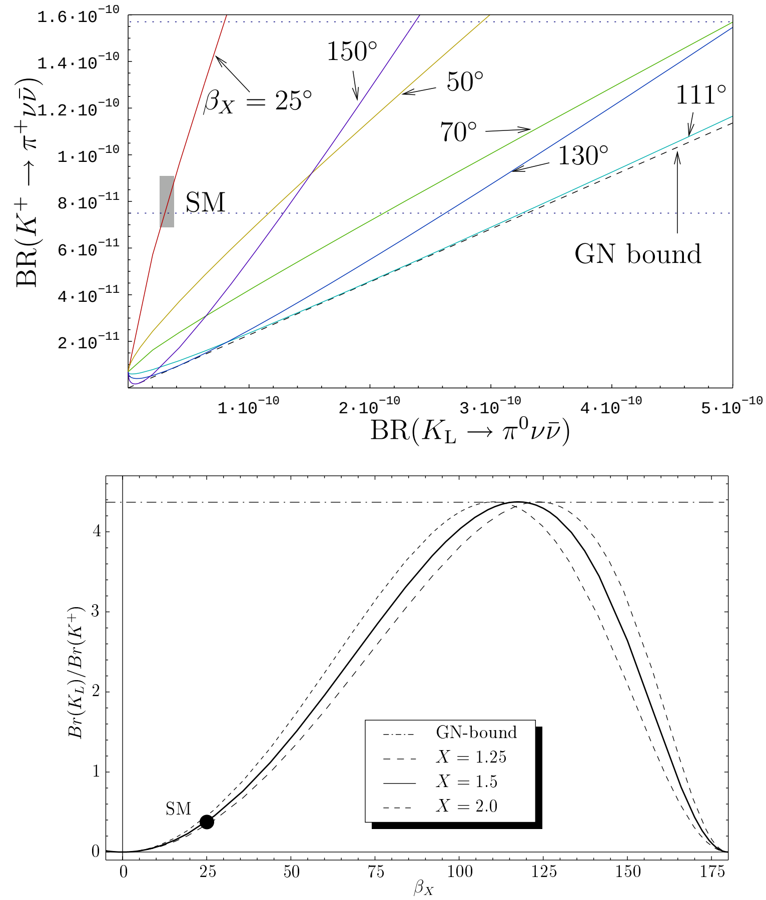

Figure 2: Up: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ as a function of $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ for various values of $\beta_X = \beta - \theta_X$ [34]; the dotted horizontal lines indicate the lower part of the experimental range (1.3); the SM range and the bound (1.4) are also indicated. Down: ratio of charged and neutral branching ratios as a function of β_X for $|X| = 1.25,\ 1.5,\ 2.0$ [9].

the effective couplings are usually much smaller in more realistic models. Nonetheless, even in the most pessimistic case, namely within MFV models, a 10% measurement of $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ allows probing new-physics scales well above the electroweak scale.

An explicit example

As pointed out in [34], a scenario with a large phase $\theta_X \approx -90°$ and a slightly enhanced $|X|$, has an interesting phenomenological motivation: assuming this effect is flavor-universal, it would provide a much better fit of recent $B \to \pi K$ data from B factories. According to this hypothesis, one would find

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (7.5 \pm 2.1) \cdot 10^{-11}\ , \quad \mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = (3.1 \pm 1.0) \cdot 10^{-10}\ , \qquad (3.5)$$

to be compared with the SM predictions in (1.1) and (1.2).

Apart from its phenomenological motivation, this explicit example is useful for illustrating two important points:

- The values of $|X|$ and θ_X of this scenario have been derived by fitting a $10-20$ % deviation in the branching ratios of $B \to \pi K$ decays. This small effect in B physics, translates into an order of magnitude enhancement of $\mathcal{B}(K_\mathrm{L} \to \pi^0 \nu\bar{\nu})$ over its SM estimate. This happens because $K \to \pi\nu\bar{\nu}$ amplitudes are completely dominated by short-distance electroweak dynamics and thus are very sensitive to possible non-standard effects above the electroweak scale. On the contrary, short-distance effects in non-leptonic B decays are largely *diluted* by sizable long-distance contributions, which are insensitive to physics above the electroweak scale.

- $\mathcal{B}(K_\mathrm{L} \to \pi^0 \nu\bar{\nu})$ is naturally more sensitive to new physics than $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$. In particular, in this specific case $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ does not significantly differ from the SM estimate. This happens because the enhancement of $|X|$ and the effects of large θ_X, while being constructive in the $\mathcal{B}(K_\mathrm{L} \to \pi^0 \nu\bar{\nu})$ case, compensate each other in $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$.

It is worth stressing that, in spite of the phenomenological character of the analysis of [34], such a configuration can be realized within consistent extensions of the SM. In particular, as noted first in [35], and as confirmed by more recent detailed analyses [36, 37], a scenario of this type can be explicitly realized within low-energy supersymmetric extensions of the SM.

3.3 Testing specific models: the MFV hypothesis

As we have seen in the previous section, the $K_\mathrm{L} \to \pi^0 \nu\bar{\nu}$ decay is in principle sensitive to new physics up to very high scales. However, this is true only in non-standard scenarios where the additional contributions to $K \to \pi\nu\bar{\nu}$ amplitudes do not respect the strong CKM suppression present in the SM and are not governed by the GIM mechanism. A similar behavior occurs in many other FCNC transitions, although the maximal sensitivity reachable in B decays is substantially smaller than the one in (3.4). For this reason, when discussing new-physics effects in rare FCNC processes, it is very convenient to distinguish two basic scenarios: i) models with new sources of CP violation and flavor mixing; ii) models where, at the electroweak scale, these symmetries are effectively broken only by terms proportional to the (SM) Yukawa couplings. The latter is usually called hypothesis of Minimal Flavor Violation (MFV) [29, 30]. As shown in [30], this hypothesis can be formulated in a consistent way (in terms of an effective field theory), even without specifying the details of the new-physics model. It can also be shown that

this hypothesis is the most pessimistic framework for rare decays: given the Yukawa interaction breaks CP invariance and induces flavor mixing already within the SM, we cannot impose a more restrictive symmetry-breaking pattern beyond the SM [30].

The consequences of the MFV hypothesis for $K \to \pi\nu\bar{\nu}$ decays have been discussed by several authors (see [9, 38] and references therein), both in general and in specific frameworks where this hypothesis can naturally be implemented (such as low-energy supersymmetry, universal extra-dimensions, little-Higgs models, etc.). On general grounds, the MFV hypothesis forces $K \to \pi\nu\bar{\nu}$ amplitudes to be proportional to the CKM factor λ_t. Thus, in these models the new-physics scale probed by $K_{\rm L} \to \pi^0\nu\bar{\nu}$ is in the few TeV range, as can easily be understood by setting $\mathrm{Im}\lambda_{sd} = \mathrm{Im}\lambda_t$ in (3.4). Within all SM extensions which provide a natural solution to the hierarchy problem, this is the natural scale for new physics to show up.

An interesting virtue of MFV models is that they allow a simple comparison of new-physics effects in different observables in B and K decays. This is because the new contributions are essentially flavor-universal, with a relative weight in B and K decays controlled only by the CKM matrix. An example of this comparison is shown in Fig. 3. As can be noted, the exceptional theoretical cleanness of $\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})$ makes it the most effective probe of new physics among rare decays.

Other general consequences of the MFV hypothesis, which could easily be verified or falsified by precise measurements of $\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})$ (or the two $K \to \pi\nu\bar{\nu}$ rates), are listed below:

- The golden relation (2.4) must be satisfied. As a result, given the values of $\sin 2\beta$ and $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$, only two values of $\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})$ are possible in the full class of MFV models, independently of any new detail of the specific framework [43]. They correspond to X being positive or negative. The latter sign is very unlikely [31].

- The 95% probability upper bound reads $\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu}) \leq 4.6 \cdot 10^{-11}$ [31].

Apart from these general properties which hold in all MFV models, some framework-dependent results, which have been discussed in the recent literature, could also be very useful to support or exclude specific scenarios:

- within the flavor-blind MSSM [39], $\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})$ is generally smaller than in the SM;

- within the model with one universal extra dimension discussed in [42], one finds $\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu}) \leq 4 \cdot 10^{-11}$;

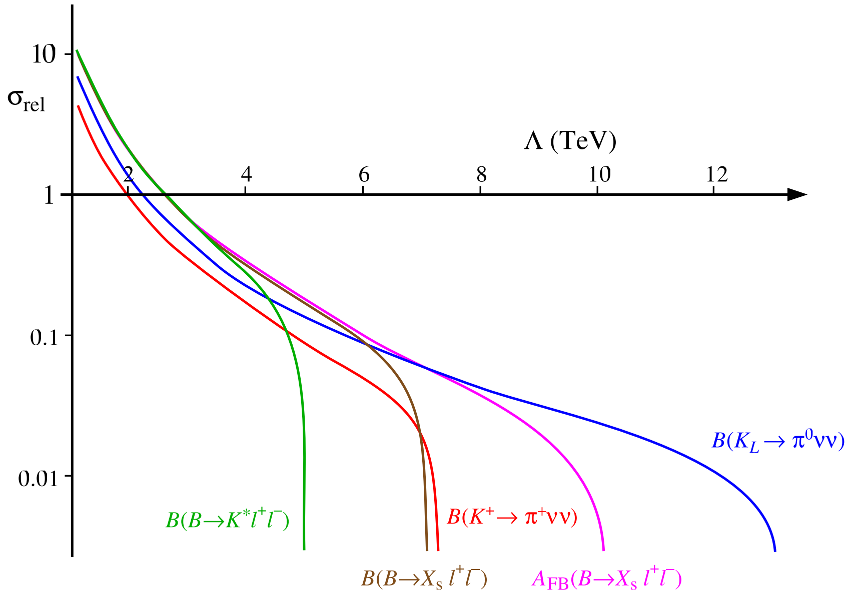

Figure 3: Comparison of the effectiveness of different rare observables in setting future bounds on the scale of the representative operator $(\bar{Q}_L Y_U^\dagger Y_U \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$ within MFV models [30]. The vertical axis indicates the relative precision of a hypothetical measurement of the observable with central value equal to the SM expectation. All the curves are obtained assuming a 1% precision on the corresponding overall CKM factor.

- within the so-called littlest-Higgs model, $\mathcal{B}(K_\mathrm{L} \to \pi^0 \nu\bar{\nu})$ could saturate the $6 \cdot 10^{-11}$ bound according to [40]. On the other hand, in [41] only deviations from the SM by at most 10% have been found. This discrepancy should be soon clarified.

3.4 Beyond MFV

The possibility of new sources of CP violation and flavor mixing in the $1 - 10$ TeV region is, in principle, the most natural possibility. At present, this scenario is challenged by the precise SM-compatible results in B physics. However, a large portion of the allowed parameter space is still to be explored: on the one side, it is clear that we cannot have $O(1)$ flavor mixing beyond the SM (if new degrees of freedoms will show up in the TeV region, as suggested by a natural solution to the hierarchy problem); on the other side, it is far from being obvious that the SM Yukawa couplings are the only source of flavor-symmetry breaking (as assumed within the MFV hypothesis). Precise measurements of the $K \to \pi\nu\bar{\nu}$ rates are a key element to address this problem in a model-independent and quantitative way.

Models with new sources of CP violation and flavor-symmetry breaking usually in-

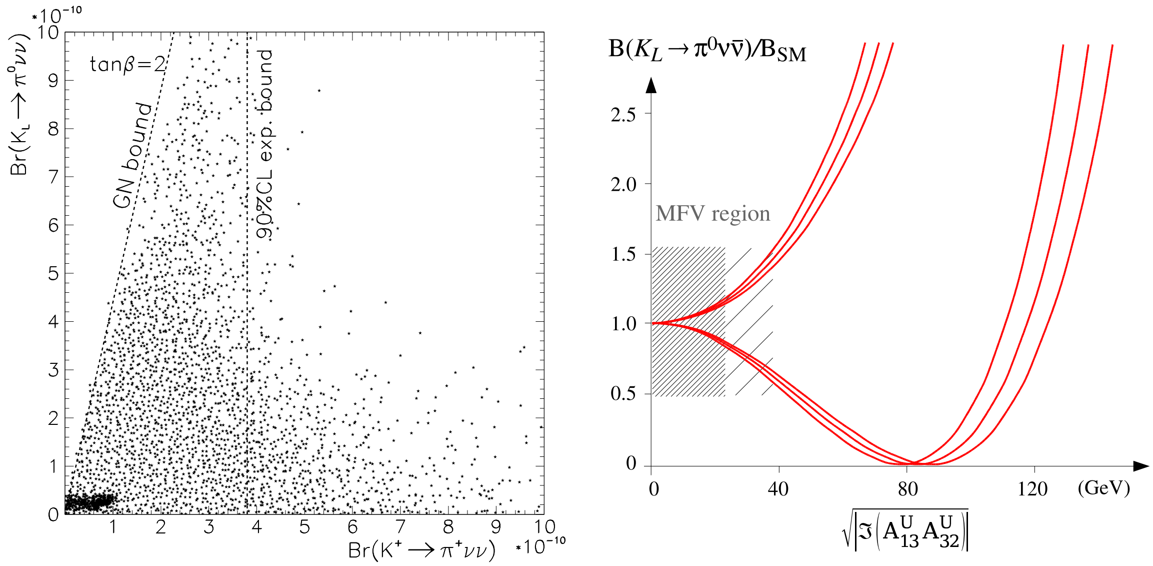

Figure 4: Left: $\mathcal{B}(K_\mathrm{L} \to \pi^0 \nu\bar{\nu})$ vs. $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ as obtained by a scan of the allowed parameter space of the MSSM with generic flavor couplings [37]. Right: Prediction [44] of $\mathcal{B}(K_\mathrm{L} \to \pi^0 \nu\bar{\nu})$ as a function of the soft-breaking trilinear couplings A^U_{13} and A^U_{32}, at fixed values of squark and chargino masses ($\tilde{m}_L = 500$ GeV, $\tilde{m}_R = 300$ GeV, $\tilde{m}_{\chi^\pm} = 200$ GeV, with $\pm 5\%$ uncertainty). Here the two branches correspond to the two possible signs of the overall MSSM coupling.

volve large numbers of new free parameters that are impossible to fix using only one type of experiment. In this case, the information from $\mathcal{B}(K \to \pi\nu\bar{\nu})$ is fully complementary to the information extracted by direct searches at high energies, which are crucial to determine masses and dominant couplings of the new particles. The high-energy information is not sufficient to fix the (presumably tiny) new effects of CP violation and flavor mixing: as in the SM, these effects can be fully determined only with the help of rare decays.

Among the various models of this type which have been discussed in the literature, the most representative and most popular is probably the MSSM with generic flavor couplings (for a comprehensive analysis of $K \to \pi\nu\bar{\nu}$ decays in this framework, see [37] and references therein). A few important properties which emerge in this context, which are also valid in non-supersymmetric models, are listed below:

- Even after taking into account all the available constraints from CP-violating observables and rare decays, there is still much room for possible enhancements in $\mathcal{B}(K_\mathrm{L} \to \pi^0 \nu\bar{\nu})$ (and also in $K^+ \to \pi^+ \nu\bar{\nu}$). The typical range in the MSSM is illustrated by the left plot in Fig. 4.

- Large effects in $K \to \pi\nu\bar{\nu}$ are possible because the electroweak structure of the corresponding decay amplitudes is quite different from that of $\Delta F = 2$ processes ($K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$) and $\Delta F = 1$ magnetic transitions ($b \to s\gamma$). As a result, within the MSSM $K \to \pi\nu\bar{\nu}$ amplitudes are strongly sensitive to the trilinear soft-breaking terms in the up sector, which are poorly constrained by other observables [28, 33, 35]. As illustrated by the right plot in Fig. 4, a precise measurement of $\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})$ would provide a very stringent constraint on these fundamental couplings of the MSSM, which are weakly constrained by other sources.

- The possible values of $\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})$ in this general framework are not necessarily above the SM prediction: in this context it is also possible to obtain a vanishing small $K_{\rm L} \to \pi^0\nu\bar{\nu}$ rate (contrary to the MFV case, where the experimental evidence of the $K^+ \to \pi^+\nu\bar{\nu}$ mode also implies a non-vanishing $K_{\rm L} \to \pi^0\nu\bar{\nu}$ rate).

- In the presence of new sources of flavor mixing the golden relation (2.4) is naturally broken.

To conclude this section, we note that possible large deviations from the SM in the two $\mathcal{B}(K \to \pi\nu\bar{\nu})$ have also been discussed recently in more exotic scenarios, such as supersymmetric models with broken R parity [45], models with extra Z' bosons [46], or models with extra vector-like or isosinglet quarks [47]. A complete list of references can be found in [9].

4 Experiments Seeking $K_{\rm L} \to \pi^0\nu\bar{\nu}$

The experimental signature for the $K_{\rm L} \to \pi^0\nu\bar{\nu}$ decay mode consists of exactly two photons with the invariant mass of a π^0, and nothing else. The experimental challenge arises from the 34% probability that a K_L^0 will emit at least one π^0 in comparison with the expected decay probability for $K_{\rm L} \to \pi^0\nu\bar{\nu}$ which is ten orders of magnitude smaller. The most difficult decay channel to suppress is the CP-violating channel $K_L^0 \to \pi^0\pi^0$, which has a branching ratio of $0.9 \cdot 10^{-3}$ [48]. Compounding the problem, interactions between neutrons and kaons in the neutral beam with residual gas in the decay volume can also result in emission of single π^0s, as can the decays of hyperons which might occur in the decay region, *e.g.* $\Lambda \to \pi^0$n. Virtually any experimental approach must rely on an extremely high level of photon detection efficiency, at least as good as the best yet achieved in E949, the study of $K^+ \to \pi^+\nu\bar{\nu}$, at BNL [15]. However, due to limitations in the level of achievable efficiency due to physical processes such as photonuclear interactions and pile-up effects, a firm observation of $K_{\rm L} \to \pi^0\nu\bar{\nu}$ at the expected level requires some additional handles for suppressing backgrounds.

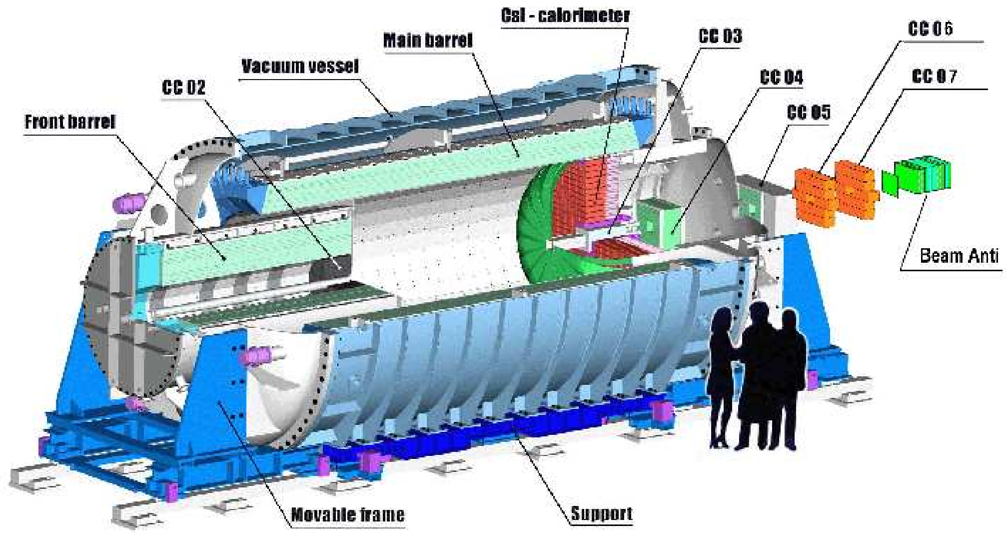

Figure 5: E391a $K_L \to \pi^0\nu\bar{\nu}$ detector at KEK[49]. The neutral beam enters from the left.

The current experimental limit $\mathcal{B}(K_\mathrm{L} \to \pi^0\nu\bar{\nu}) \leq 5.9 \times 10^{-7}$ [16] comes from the KTeV experiment at Fermilab, which employed the Dalitz decay $\pi^0 \to \gamma e^+e^-$ with charged particles in the final state to obtain a better signature for suppressing backgrounds. The two order of magnitude penalty incurred by the $\pi^0 \to \gamma e^+e^-$ branching ratio rules out this method for high sensitivity searches. Considerable improvement in sensitivity is anticipated by E391a [49] which has recently taken data at the 12 GeV Proton Synchrotron at KEK. The detector is shown in Fig. 5. The experiment employs a highly collimated "pencil" beam to provide transverse constraints on the origin of the π^0. The beam enters a cylindrical veto barrel designed to eliminate background from upstream decays. Photons from signal π^0's decaying in the main barrel are detected in an array of high-resolution pure CsI modules. Lead-scintillator shower counters occlude all angles not covered by the CsI or the incoming beam, so that there is nearly hermetic veto coverage. Events with two clusters in the CsI unaccompanied by other detector activity are fit assuming they emanate from a π^0 decaying in the beam. This allows the determination of Z-vertex and transverse momentum values for the π^0. Cuts on these quantities are designed to distinguish signal from background. E391a is intended to serve as a pilot for a possible more sensitive experiment to be mounted at J-PARC[50].

KOPIO is a new experiment at the BNL AGS which seeks to observe and study $K_\mathrm{L} \to \pi^0\nu\bar{\nu}$ if it occurs at the SM level or even well below the SM prediction. The extra handle that makes a robust experiment feasible is the measurement of the K_L^0 momentum

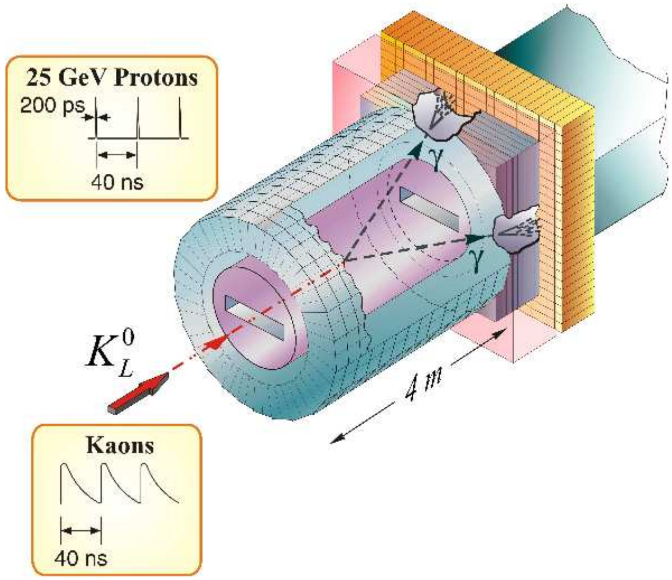

Figure 6: Schematic representation of the KOPIO apparatus and technique. The neutral kaon beam is produced by a 25 MHz micro-bunched proton beam striking a production target. Kaons decaying via $K_{\rm L} \to \pi^0\nu\bar{\nu}$ in the detector region are detected by the presence of photons from π^0 decay which convert and are tracked in the photon pointing calorimeter or "preradiator" so that the K_L^0 decay vertex can be determined.

using time-of-flight (TOF) (see Fig. 6). Copious low energy kaons can be produced at the BNL AGS in an appropriately time-structured beam. From the knowledge of the decaying K_L^0 momentum, the π^0 can be transformed to the K_L^0 center-of-mass frame and kinematic constraints can be imposed on an event-by-event basis when the π^0 decay photon directions are measured. This technique facilitates rejection of other kaon decay modes and suppression of all other potential backgrounds, including otherwise extremely problematic ones such as hyperon decays and beam neutron and photon interactions.

The required level of background suppression will be achieved using a combination of hermetic high sensitivity photon vetoing and full reconstruction of photons through measurements of timing, position, angle, and energy. Events originating in the two-body decay $K_L^0 \to \pi^0\pi^0$ identify themselves when reconstructed in the K_L^0 center-of-mass system once two photons have been observed. Furthermore, those events with missing low energy photons, the most difficult to detect (due, in part, to possible photo-nuclear interactions), can be kinematically identified and eliminated. With the two criteria based on precise kinematic measurements and demonstrated photon veto levels, there is sufficient experimental information so that $K_L^0 \to \pi^0\pi^0$ can be suppressed, and the background level can also be measured directly from data.

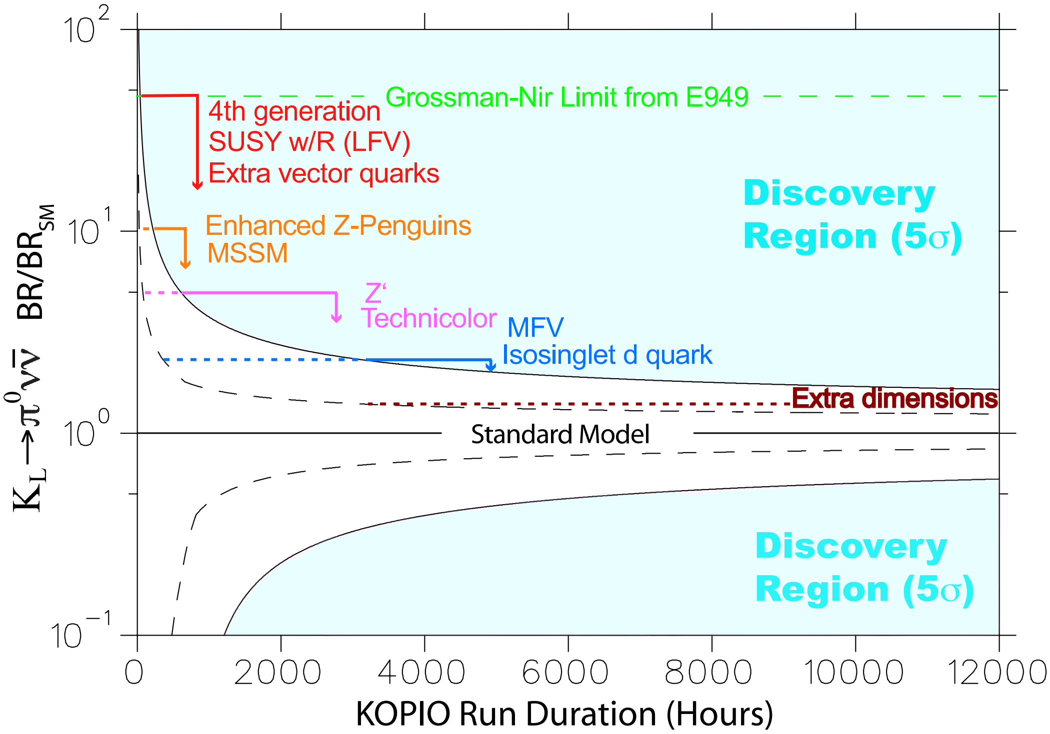

Figure 7: 5σ discovery region (shaded area) and 95% CL upper and lower exclusion limits (dashed lines) versus running time for the KOPIO experiment. For comparison, the maximal enhancements of $\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})$ expected in various non-SM scenarios (see Section 3) are also indicated.

Evaluation of the KOPIO system leads to the expectation that $\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})$ could be measured with a precision of 10% or better if the SM prediction holds; this would result in a measurement of $|{\rm Im}\lambda_t| < 5\%$. If non-SM physics results in a larger rate, as discussed above, the precision on the branching ratio would be correspondingly better.

As the experimental sensitivity increases, in the absence of a positive signal, non-SM branching ratios closer and closer to the SM can be eliminated. To illustrate the general situation, it is instructive to use the ultimate reach of an experiment like KOPIO where a five standard deviation (5σ) discovery could be firmly established for branching ratios outside the region $(0.59 - 1.65) \times \mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})_{\rm SM}$. For shorter runs, the range that can be explored is somewhat smaller [3]. A plot of the 5σ discovery region and of the 95% CL exclusion limits as a function of running time is given in Fig. 7.

Although specific to KOPIO, this figure illustrates an interesting generic feature

[3]For example, after the 6000 hours of operation in the present plan for KOPIO, a 5σ discovery could be made outside the region $(0.48 - 1.91) \times \mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})_{\rm SM}$

of any experiment designed to span orders of magnitude in searching for a rare process. First, because the background rejection power of the experiment must be sufficient for the ultimate sensitivity, for the early part of the running, the background will be negligible and progress in ruling out (or discovering!) branching ratios far above the expected level is very swift and will be nearly linear in running time. After the initial period, to a good approximation, further progress becomes proportional to the square root of the running time. It is also notable that in any experiment with a significant amount of background present along with the signal, to bound the branching ratio from below requires a substantial amount of running. In the KOPIO case, the existence of a SM signal at the five sigma level would be established after about 1000 hours into the run.

5 Conclusions

The rare decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_{\rm L} \to \pi^0\nu\bar{\nu}$ are both extremely suppressed within the SM and exceptionally clean –from the theoretical point of view– both in the SM and in most of its extensions. For these combined reasons these processes play key roles in the search for physics beyond the SM. In particular, their measurements offer unique tools to deeply investigate the CP violation and flavor breaking structure of any extension of the SM. Being completely dominated by (one-loop) electroweak dynamics, the two $K \to \pi\nu\bar{\nu}$ rates may be greatly affected by new-physics contributions. However, even if the experimental measurements were found to be in agreement with the SM expectation, with a small relative error, this information would translate into a precious insight about new physics: information about the flavor structure of the model complementary to those attainable at high-energy colliders.

Although most of the theoretical virtues are shared by the neutral and charged $K \to \pi\nu\bar{\nu}$ modes, the $K_{\rm L} \to \pi^0\nu\bar{\nu}$ channel has the great advantage of being sensitive to CP violation and, as a consequence, of being more sensitive to new physics. In addition, it is the theoretically cleanest of all the accessible FCNC process involving quarks. This makes the $K_{\rm L} \to \pi^0\nu\bar{\nu}$ mode probably the most fascinating process in the field of K and B meson decays.

Experimentally, the prospects for achieving high precision measurements of $K \to \pi\nu\bar{\nu}$ decays are very promising. E787/E49 at BNL has discovered the decay $K^+ \to \pi^+\nu\bar{\nu}$ observing three events so far. Initiatives to pursue this measurement are under discussion at Fermilab, J-PARC and CERN. The latter, "NA48/3", aims at a sensitivity equivalent to a 10% measurement at the SM level [51]. Shortly, a new result from a recently completed search for $K_{\rm L} \to \pi^0\nu\bar{\nu}$ at KEK will be available and an LOI exists for J-PARC that aims at a high precision measurement[50]. The new KOPIO experiment

at BNL plans to explore branching ratios well below the SM prediction and, in the absence of new physics, would measure $B(K_{\rm L} \to \pi^0 \nu\bar{\nu})$ to a precision approaching 10% . This result would exclude many possible non-SM approaches and, on pure dimensional grounds, would place a limit above 1000 TeV on the mass scale of contributing new physics.

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